Creating autonomous spacecraft with AFAST

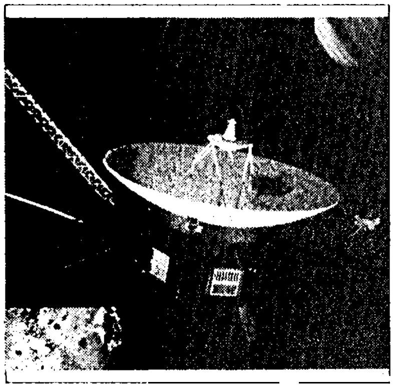
Suraphol Udomkesmalee, Guy K. Man, and Barbara A. Wilson

Jet Propulsion Laboratory, California institute of Technology
Pasadena, California 91109

ABSTRACT

Autonomous Feature And Star Tracking (AFAST), essential technology for building autonomous spacecraft that explore solar system bodies, is described. The architecture and processing requirements of the systems comprising AFAST are presented for probable mission scenarios. The focus is on celestial-scene interpretation, the implications of that interpretation for AFAST systems, and an AFAST technology status.

1. INTRODUCTION



If it works, why fix it?
(Shown: Voyager spacecraft.)

New GNC capability is needed to rendezvous with and land on small bodies.
(Shown: Lander.)

One of the means currently proposed for implementing capable, low-cost planetary exploration is an entirely new approach to spacecraft maneuvering and pointing operations: the use of onboard, autonomous target tracking based on image analysis. This type of automation has been actively pursued in automatic target-recognition research[1] for decades, but in the realm of space exploration, spacecraft autonomy has been viewed as unreliable and high risk. The success of Voyager ground-based operations and the failure of the Giotto spacecraft to successfully track the nucleus of Halley's comet (an effort which employed a simple intensity-peak detection scheme)[2] have increased the skepticism regarding implementing such onboard autonomy into costly planetary missions. Thus, ground-based processing has continued to be actively involved in generating detailed operational sequences to correct trajectories and use the spacecraft/target position knowledge to direct science pointing remotely from Earth.

There are weaknesses in relying on ground-based control of planetary spacecraft (see Fig. 1). This traditional approach has been limited by the length of round-trip communication times and by uncertainties in target positions and motions. Furthermore, we have a history of lost opportunities to conduct detailed investigations of "serendipitous" targets (such as the eruption of volcanoes on Jupiter's moon Io, the moon of Asteroid Ida, and geysers on Neptune's moon Triton), in spite of the utilization of extremely high-performance spacecraft guidance, navigation, and control (GNC) components (such as NASA-standard gyros, star trackers, imaging science cameras, JPL radio metric/optical orbit-determination systems, etc.), Onboard, autonomous target tracking will permit guidance and control of spacecraft to be based on target-relative position information and will enable exploration of "unpredictable" bodies such as comets, asteroids, and other icy bodies to be achieved with great efficiency, even if less accurate and fewer GNC components than conventional GNC components are used (note that complex mission scenarios may dictate more instruments for achieving mission objectives, but for comet/asteroid flybys and rendezvous, this assessment is valid).

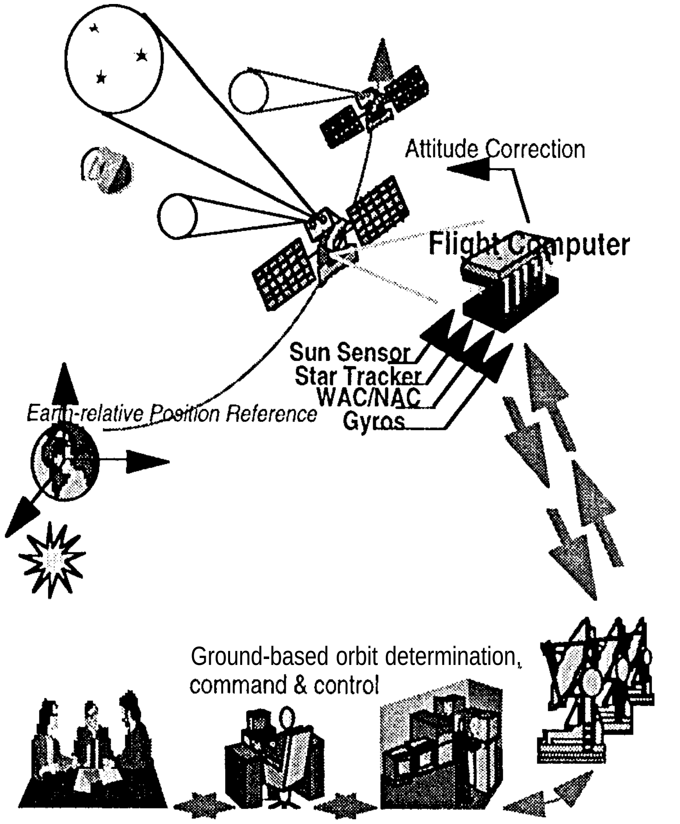
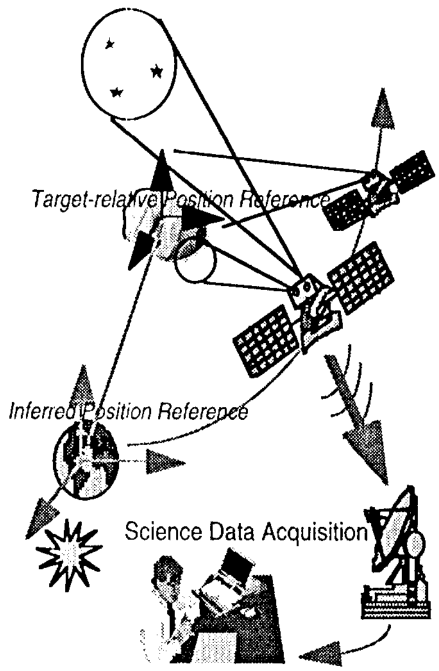
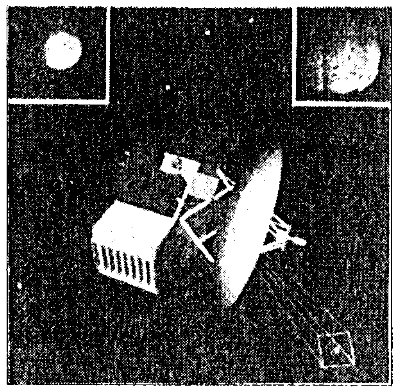


Fig. 1, Conventional guidance, navigation, and control system. This collection of high-performance sensing/processing systems provides a very accurate estimate of spacecraft relative to Earth but is unable to react to targets of opportunity.



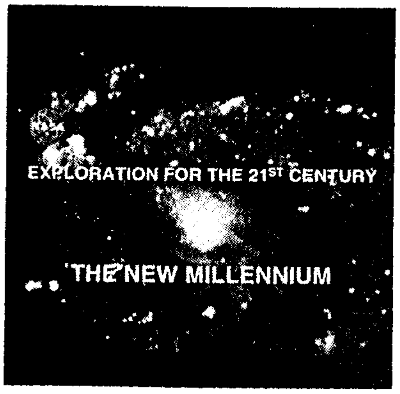
Fig, 2. Onboard celestial-reference GNC system. This small, low-cost, enabling solution for space exploration has come about because of advancements made in the onboard recognition/tracking of celestial bodies and terrain features.

Years of pioneering research and demonstrated closed-loop target-tracking capability, coupled with today's economic reality, have culminated in a new era of autonomous space exploration for the 21st century, with spacecraft/missions that cost tens of millions of dollars instead of billions, weigh tens of kilograms instead of thousands, and deliver more science than ever before. Figure 2 depicts a new GNC architecture that relies on an efficient, distributed sensing (the "eye") and commanding (the "brain") architecture to extract necessary attitude/position references and plan maneuvers/pointing on the basis of direct observation of known/targeted Solar System bodies. This target-relative position information can then be used to infer position relative to Earth, if needed, Note that because of science pointing requirements, the three-axis-stabilized spacecraft configuration is assumed. The JPL-developed Autonomous Feature And



AFAST engenders autonomous spacecraft.

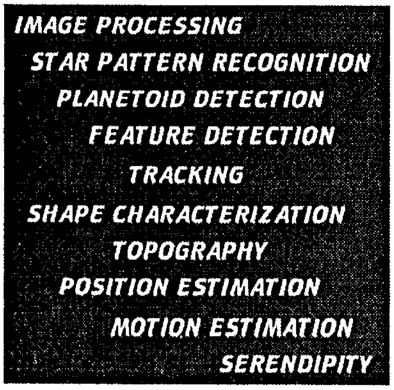
Star Tracking (AFAST) technology plays a major role in this realization by providing an intelligent "eye" for JPL's space explorers.



The New Millennium program represents a new era in spacecraft design.

Under new sponsorship by the NASA Office of Space Access and Technology in support of NASA's New Millennium (NM) program, sedulous efforts to mature AFAST technology for demonstration flights prior to the end of this century are under way. The NM program focus is the identification and flight validation of key breakthrough technologies to enable frequent, exciting, affordable Earth and space science missions in the 21st century. AFAST for NM spacecraft spans a gamut of engineering disciplines, providing sensor, processor, software, analysis, systems, and test technology, and gives rise to a new paradigm for space exploration methodology. In this paper, groundwork for the development of AFAST, as well as AFAST applications to future exploration of small bodies (comets and asteroids), will be described, and the current technology status assessed. Our main objectives are 1) to introduce AFAST to the general optical-tracking community, 2) to provide a holistic view of the problems and issues, and 3) to inspire independent or collaborative R&D work on this specialized target-tracking technology.

2. AFAST SOLUTIONS FOR CELESTIAL-SCENE INTERPRETATION



AFAST needs holistic solutions to problems of celestial-scene interpretation.

Seminal ideas and solutions to problems are the cornerstone of a general-purpose celestial-scene interpretation system that will be functional for a broad range of celestial targets (planets, moons, asteroids, comets, icy satellites, etc.), Thus, as a ground rule, ad hoc or brute-force approaches specially calibrated to provide near-term solutions for characterizing a specific target or celestial body are not recommended. Furthermore, our view of autonomy also implies that no parametric tuning/calibration will be required on board to achieve satisfactory performance in each specific mission scenario.

Our knowledge of the stars, planets, moons, and other heavenly bodies is sufficient to navigate spacecraft through the solar system using only observed images of the sky as a guide. We should not shortchange ourselves by not fully utilizing all the visual cues that can be detected by the eye of a robot explorer, and not minimizing the number of traditional GNC components (which are functionally redundant) required to carry out a mission. In this section, we briefly outline AFAST solutions to problems presented under the fundamental topics of celestial-scene interpretation. The status and maturity of the solution(s) for each problem are also given.

Image processing: Image processing is the first step toward extracting essential GNC information contained in the celestial scenes. Different types of image enhancement will be needed to highlight the various objects/features of interest (for example, stars, extended bodies, limbs, terminators, craters, etc.).

Because background and noise in space images are more tractable than terrestrial scenes, removal of spurious spots (such as photon noise) from stars can easily be done by comparing consecutive images of the same scene. The major challenge is in the attempt to extract a GNC-reference feature (or features) from proximate background terrains when viewing the feature(s) at close range. While edge-enhanced/histogram-based segmentation[4] is suitable for bringing out the limb and terminator, texture-based segmentation[5] is more appropriate for terrain features. We can tap into a wealth of proven algorithms in the computer vision field and select those that are suitable for celestial scenes and most efficient with respect to the processing/memory/control limitations of autonomous spacecraft.

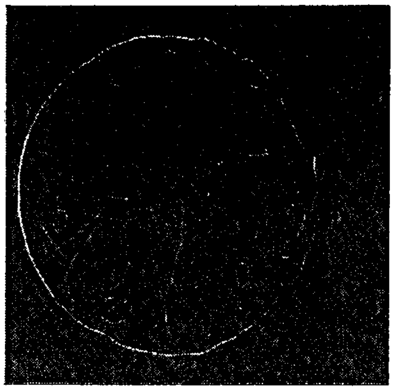
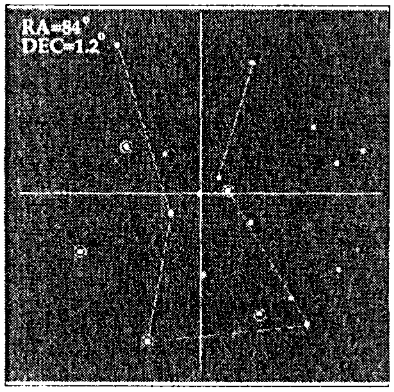


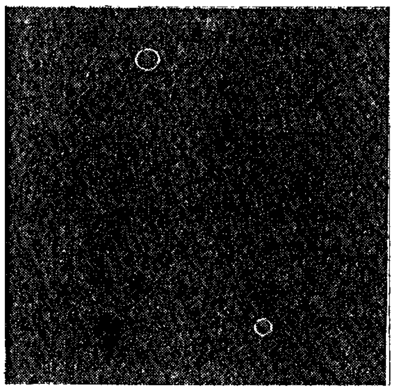
Image processing deals with target/feature enhancements and background suppression. (Shown: Edge-enhanced image of Miranda,)

Recognition of star patterns: Identifying the spacecraft inertial attitude from star patterns allows the spacecraft to orient itself properly before any planned maneuver is made. This area needs a lot more attention from pattern recognition researchers. Solutions which are based on pairwise angular distance matching,[6] are limited by the combinatorial growth of possible pairs, and thus dictate camera parameters such as field of view, accuracy, and star magnitude sensitivity. Algorithms based on efficient signature-based matching used in all-sky searches have been proposed.[7-8] In terms of robustness, efficiency, and the flexibility to cover a wide range of camera field of view and star-catalog sizes, matching to a unique signature function for each star is superior to any other approach. As we move toward dimmer stars, the density and more uniform spacing of the stars make things a bit difficult. However, with a committed effort to test and improve the current algorithms, it will not be long before we can announce a flight-proven, signature-based, star-identification algorithm.



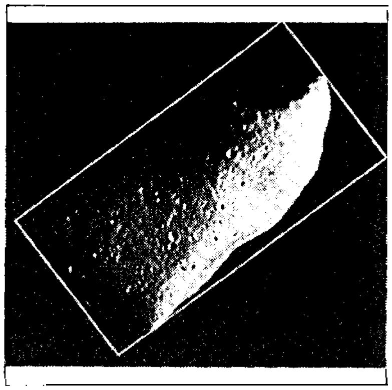
Star identification is achieved by matching the measured signature with catalog signatures.

Planetoid detection: Any solar system body (planet, moon, asteroid, comet, etc.) appearing in an image can be used to provide information about the spacecraft's position, given that the orbit of the observed body is known. If the body is significantly large, then we can simply trace edge points to determine the object's boundary.[9] The boundary-tracing technique can easily be modified to detect the presence of multiple non-eclipsing bodies.[10] If the targeted solar system body is imaged in a known pattern of stars, then the knowledge of inertial attitude, which is gained by using imaged background stars, coupled with a priori knowledge of the orbit, can be used to achieve accurate detection of other distant/small solar system bodies. Comparing homologous image information from frame to frame will probably be required to avoid false detection and errors in spacecraft orbit determination. Detection of small extended bodies is not new to ground-based optical navigation.[11-12] However, adapting the existing tools, algorithms and databases to the onboard environments of autonomous spacecraft will be a challenge.



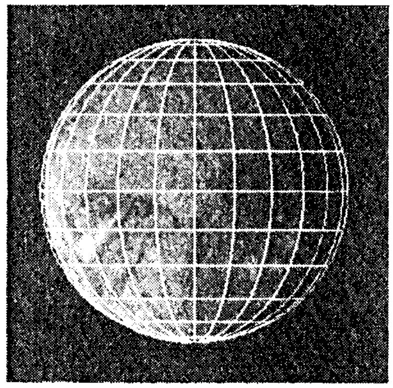
Large boundaries confirm detection of extended bodies.

or landers with autonomous GNC capability, 3-D knowledge of the object's shape will be needed to create a map that can be used for maintaining a desired orbit and selecting a hazard-free landing area. Since there will be sufficiently stable feature points to use as references for the spacecraft's position, an accurate 3-D description of irregularly shaped objects[23-24] may be overkill. On the other hand, overbounding by using a simple geometric shape like an ellipse or a rectangle will be inadequate. It is possible to derive a generic solution to shape characterization, considering that the issue here is to represent the shape with sufficient fidelity that when combined with terrain-feature knowledge, it is recognizable from the spacecraft vantage point and permits the spacecraft to use autonomous image-guided GNC operations. We have not given enough attention to this area because of our past focus on planetary flybys, but with the planned NM missions involving asteroid/comet orbiters, probes, and landers, shape-characterization capability must be matured soon in order to realize the vision of NM.



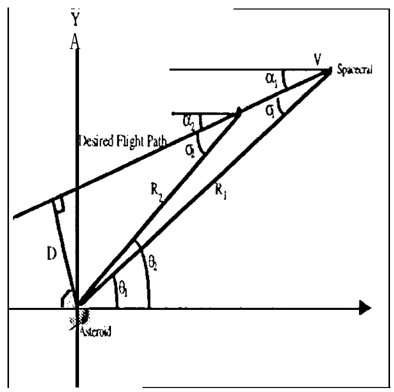
A rectangular-bounding approach is used to derive pointing commands during flybys. (Shown: Gaspra.)

Topography: Some sort of map-making capability must be implemented on board if the spacecraft is to make decisions by itself in selecting interesting regions for scientific investigations or identifying candidate landing areas, then plan the maneuver toward these sites. It has been shown that, from a series of images, scientists can approximate the shape, and sketch a map, of the surface of irregular Solar System objects.[25] We do not envision the need to employ photometric functions to describe the surface[26] because relative brightness and apparent texture, coupled with proximate feature points, should be sufficient for GNC and pointing purposes. However, without the help of human visual perception and detailed knowledge of Solar System bodies, this process will be difficult to automate. Note again that accurate mapping and accurate depictions of physical reality may not be necessary here. We just need enough information to predict where all the key features are, given the current vantage point. The facts are that we are still at an inchoate stage of formulating a solution to the problem of automating topographic mapping and that it would behoove us to evolve from a simple. solution and not to be overwhelmed by what we know about physics. Instead, tile reality of the computer visual-percept ion capability should be the driving factor for now.



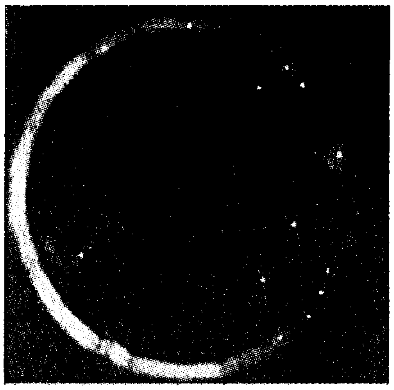
Onboard topography capability maps only distinct terrains to be used for spacecraft GNC and pointing. (Shown: Miranda.)

Position estimation: Since target-relative information is required for the new GNC paradigm, the visual feedback is designed to provide spacecraft information (with respect to the target body) for **AV** maneuvers and control, Note that attitude and rate information is readily available from stellar references and gyros. It is safe to assume a rigid (non rotating) body here, since changes caused by spacecraft motions are much more prominent than rotations of the targeted Solar System object. AFAST has not yet addressed this topic (monovision position estimation from a



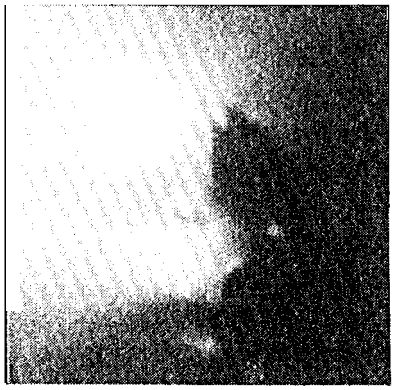
Target-relative position based on direct observations closes the loop for spacecraft GNC.

Feature detection: Important features required for accurate estimation of the position and/or motion of a target are limbs and terminators. An efficient way to bifurcate limb/terminator segments from boundary points, that of locating the harmonized segment (on the limb side) in the parametric equations of the boundary curve has been suggested. *[3] However, in close-up images, the only available GNC references are terrain features. From the spacecraft GNC point of view, it is not important to recognize/classify typical geological features (such as impact craters, fluvial channels, volcanic flows and vents, erosion surfaces, eolean deposits, etc.), as long as the same feature, once registered in the computer-vision knowledgebase, can be recalled and recognized in subsequent observations. From the scientific point of view, such classification will probably require multispectral information] and human deductive logic, so it will be better left to planetary scientists, who have the unlimited resources of ground-based computing power and databases. Thus, our task here is to ensure that clearly defined features useful to spacecraft GNC and of scientific value can be detected and prioritized in some systematic way. Feature detection using 2-D Gabor elementary function[14] has been shown to be effective for detecting topographical y distinct features such as craters and noticeably bright/dark regions.[15] Detection of planetary terrain features by means of a gray level cooccurrence matrix was also tested experimentally.[16] Although we are stil 1 formulating a robust approach to the feature-detection problem, experience tells us that featureless Solar System bodies are unlikely and suggests that we can always find interesting and stable featu es on the surface for position-reference and scientific-observation purposes.



Texture-based feature detection, which highlights distinct regions is used for GNC and science.
(Shown: 2-D Gabor image of Miranda.)

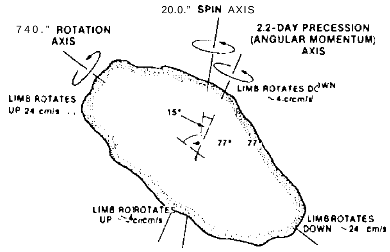
Tracking: Once feature points are identified and described, tracking these points from one image frame to another can be achieved by repeating the detection process and using the established point-to-point correspondence between feature points in successive frames to determine translational and orientation shifts.[17] This is, of course, computationally more demanding than conventional correlation tracking,[18] which was found to be unreliable in our applications because of lighting variations and terrain uncertainties.[19] A new methodology extending Kalman filter-based target tracking[20] to handle irregularly shaped objects and accurately modeled spacecraft trajectories and kinematics may be the answer here. This solution will provide a more robust performance when one is dealing with a cornet having dynamically changing and overwhelming background coma, like Halley's Comet.[21] Our progress in tracking has been steady, and the maturity of our work in this area can be expected by the end of 1995.



Robust tracking of comets may possibly be achieved via an extended Kalman filtering technique.
(Shown: Halley's Comet.)

Shape characterization: **To** plan a spacecraft maneuver around, or capture a high-resolution mosaic of, the targeted celestial body, some understanding pertaining to the shape of the object is essential. Depending on the mission objective, different levels of shape characterization will be required. For flybys, 3-D shape reconstruction is probably unnecessary, and "overbounding" generalizing the shape as a circle, an ellipse, or a rectangle will bc sufficient to maximize science return dui ing the brief encounter period.[22] For orbiters sequence of observations). However, a lot of work in this area has been done in the robot vision arena.[27-28] An estimation of the time-to-collision parameter[29] from the optical flow will also be useful during descent and landing. What we will need to add to the established computer/robot vision field is the ability to observe and estimate from long range (hundreds of thousands of kilometers). Since the spacecraft will be traveling at 10-15 km/sec, AV maneuvers must be made early on to minimize fuel consumption and maintain a desired course during approach—one that allows for optimum observation coverage and maneuverability. Incorporation of a priori velocity and target-size knowledge may be necessary for early-on missions, which will minimize future risk and allow time to gain crucial celestial-targeting experience needed for realizing the full potential of visually guided systems.

Motion estimation: For our applications, this area implies target motion factors (spin axis, precession, and rotation period) of the observed Solar System objects. Since we cannot assume a stationary observing platform here, the problem is a well-recognized conundrum. 'I'he fact that the rotation of Halley's Comet has not been resolved given a wealth of data from the Giotto, Sakigake, Suisei, Vega-1, and Vega-2 missions[21] should not deter us from attacking the problem. We believe that by having all the AFAST capabilities on board, information pertaining to the motion of the target body can be utilized more efficiently because of the ability to lock onto and examine key features and shapes and detect changes, given knowledge of the Sun illumination and spacecraft viewing directions. However, significant progress in work done in the previously mentioned AFAST topic areas and in computer vision's dynarnic-scene analysis[30] must be made before we can reify this capability. At the current time, we can take comfort in the fact that the NM program will not need this capability for missions planned before the year 2000.



Motion estimation can be done by examining the position changes of features and the Sun direction.
(Shown: Rotation model for Halley's Comet,)

Serendipity: If there is one aspect that makes AFAST different from any computer vision system, it is serendipity. How can we define what we have never seen before? At this point in time, there is a lack of flight experience, and since flight experience will be essential in evolving this capability, major breakthroughs in serendipity probably will not be made until the 21st century. Unlike other AFAST capabilities, which are GNC-driven, this area is driven by the desire to maximize science return during autonomous exploration of Solar System bodies. Initial recognition of targets of opportunity may be restricted to detecting only unexpected satellites around the target body, dynamic features on the surface such as storms, plumes, geysers, etc., and geometrically symmetric features (all of which we know how to detect given the state of the art of visual perception). It is ironic that the quintessential aspect of AFAST (serendipity) is being put off in favor of topics that share corm non ground with computer/robot vision. But until we get a good handle on the issues that directly impact autonomous GNC, this capability will never become a reality.

3. AFAST SYSTEMS

Having advanced visual perception capability (which is equivalent to the human eye and some functions of the brain) for spacecraft, we can now address the machinery physically needed to contruct AFAST systems. The interface between AFAST and the GNC subsystems—which deals with commanding, fusion of sensor data, control, and data management (serving the brain and motor functions, to use the analogy)—must also be addressed. In this section, we describe AFAST from a systems point of view (hardware; analysis and software; integration and verification). In addition, revolutionary celestial-sensing concepts known as the Celestial Eye (CE) and Electro-optic Guidance Sensor (EGS) are briefly discussed.

3.1 AFAST

Figure 3 depicts the disciplinal breakdown of AFAST. Advanced feature recognition/tracking, which is the foundation of AFAST, was described in detail in the previous section. The sensing hardware includes optics, electronics, a processor, and packaging, all forming a visual sensing/perception device that makes possible an autonomous celestial-reference GNC system. The analysis and software system provides the flight software architecture, implements algorithms, assesses performance, and provides focal plane simulations via a graphics testbed. The commanding, operation, and interfacing system mostly addresses system-engineering issues, two of the more important being interfaces with the navigation/pointing functions that incorporate all available information (such as rates, acceleration, a priori position/attitude, and other spacecraft parameters) for planning of maneuvers/turns and the processing partitioning between sensing hardware and the GNC computer. Fundamental visual-perception processing should be done in the sensing hardware, and processing that requires spacecraft information in addition to images should be done in the GNC (flight) computer. Hardware/software requirements for sensing hardware compatible with candidate NM missions should come out of this system framework. Finally, the integration and verification system creates on Earth experiments that evaluate. AFAST systems' closed-loop performance with representative stimuli generated by the GNC system and celestial environments. These experiments can be performed in both laboratory and terrestrial flight setups, and if they are carefully done, we can evolve the AFAST systems to their full capacity much faster than if we rely only on space flight experiences.

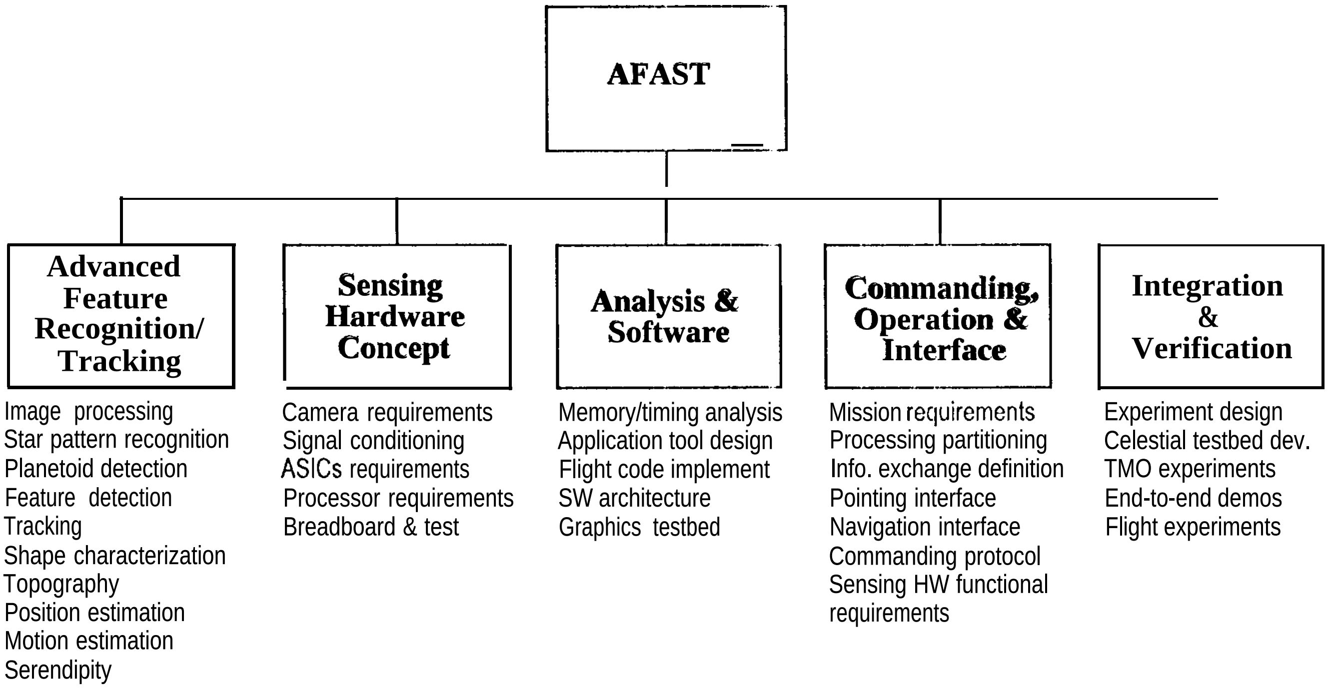


Fig. 3. Description of AFAST systems. This integration of various engineering, disciplines identifies the machinery needed for the visual-perception and decision-making capabilities of autonomous spacecraft.

Figure 4 depicts the concept of an ideal control system for NM spacecraft. This minimal configuration employs gyros to stabilize the "eye" (camera) to sense visual cues from Solar System bodies and stars. (Since some of these objects will be quite dim, holding the camera steady is critical for the fidelity of the image needed for extracting guidance information.) The control loops for both spacecraft attitude and translation can be closed through a visual-sensing device. The sensing system should be designed for efficient computation of image data (which should be a 2-D array), while the flight computer where the GNC functions reside should be optimized for data handling and information retrieval (since all the a priori knowledge of the heavenly bodies will be stored there). Essential elements of the sensing system have to be programmability and adaptability. As the knowledge concerning the celestial environments improves with observations, the flight computer must be able to redirect or adapt the "eye" to look for both expected and unexpected occurrences as needed to complete the mission.

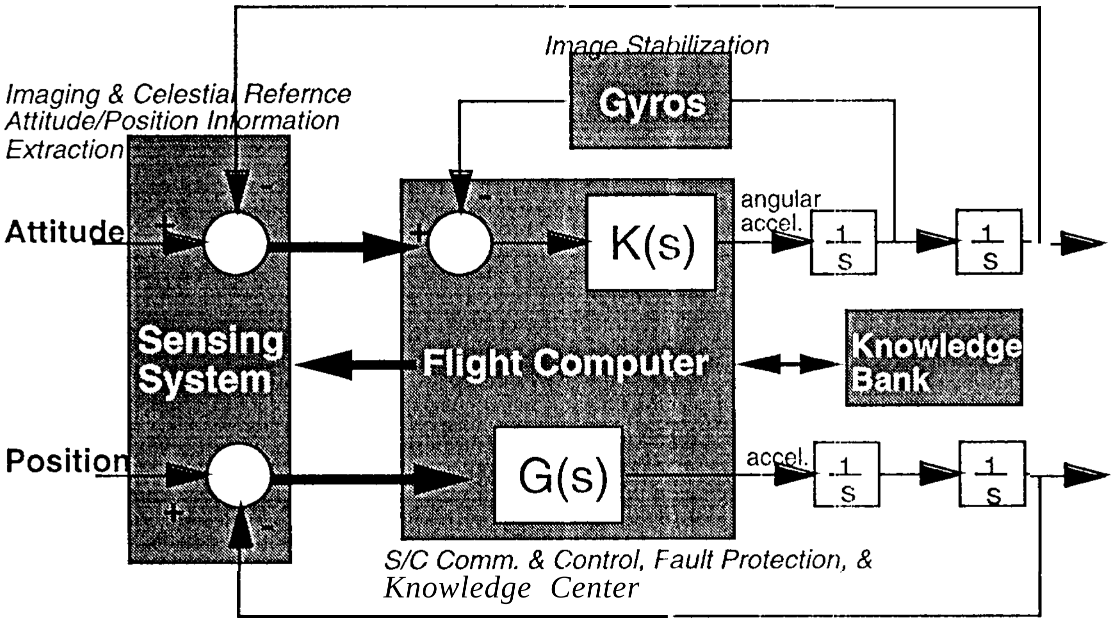
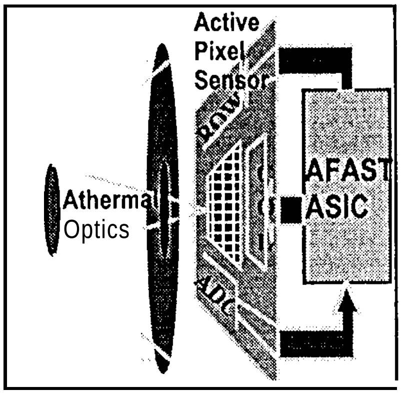


Fig. 4. Control system block diagram. 'I'he information exchange between the image-sensing system and the GNC system, which involves command instructions, a priori celestial body knowledge, and extracted attitude/position information, creates an efficient distributed architecture for perception-and-control processing in the autonomous spacecraft.

3.2 CE

Having a low-mass, high-performance, GNC-driven, celestial-target-sensing system integrating a CMOS active-pixel detector array, athermal optics and processing system[3]1 to achieve autonomous recognition of star patterns/planetary features and autonomous estimation of spacecraft attitude/position, the CE can replace the traditional combination of Sun sensor, star tracker, wide-angle. camera, narrow-angle camera, radio metric measurements, and processing system currently required to establish the knowledge of spacecraft position and attitude. This is a revolutionary concept, unlike that of any celestial sensor that has ever been flown or built before. All the information germane to the knowledge of spacecraft attitude and position will be fully exploited. Previous notions of the benefit of the ability to reject bright extended bodies in a star-tracking system are now changed. Any extended body in the field of view means

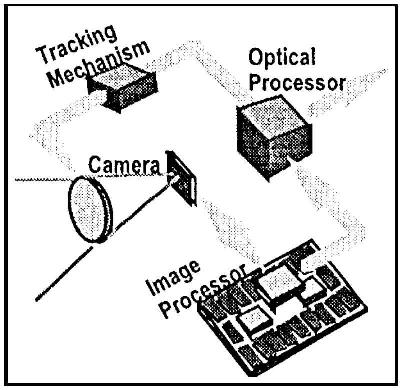


The Celestial Eye provides stellar compass, feature-tracking, and terrain cartographer capabilities in autonomous spacecraft.

spacecraft position and heading knowledge, and recognition/tracking of such a body in conjunction with stellar references must be performed. Besides being low-cost, low-mass, and low-power, the CE represents an order-of-magnitude improvement in terms of functionality over the most capable star-tracking system being assembled to date (for example, the Cassini stellar reference unit) .32

Two critical issues are the field-of-view and star magnitude sensitivity for the CE. Our vision for the long-term CE is to have a single camera that fulfills both the optical navigation and attitude-referencing requirements. This is a cause célèbre, since optical navigation typically deals with fields less than 10 and stars down to 10th magnitude, but the preference in attitude determination is for fields greater than 10° and stars brighter than 6th magnitude. To minimize the number of design parameters that we need to consider, let's just assume that the array size is given—it will be either 512 x 512 pixels or 1024 x 1024 pixels). Given these opposing requirements and our current way of controlling spacecraft, logic would imply that we will need more than one camera. However, progress in star-sensing hardware and software is being made, and all-sky identification of a "dim" star field (9th magnitude stars) is within reach. In addition, by having spacecraft position estimation done on board, updates of the position (based on observing known Solar System bodies) can be made more often, and errors associated with fewer observations and delays in ground-based processing are thus greatly reduced. Given this trend (i.e., toward attitude referencing accommodating dimmer stars, and relaxation of navigation tolerances), we may satisfy optical navigation and attitude control requirements with a CE that has a 3° field, 9th magnitude star sensitivity, and all the processing building blocks needed to handle extended bodies, including feature recognition/tracking.

3.3 EGS



The Electro-optic Guidance Sensor provides extended-range, high-bandwidth guidance signals for probes/landers.

So far all the AFAST processing and hardware implications connote a system bandwidth slower than 1 Hz. To hover near, intercept, or land on comets/asteroids will require a much faster control system. An optical tracking system combined with an active ranging device to provide line-of-sight and range signal feedback for GNC during descent and landing[33] is impractical for cornet/asteroid landings by the NM spacecraft. Proper guidance must occur at an early stage of descent and cover a range which will be many orders of magnitude over the feasible range of a laser rangefinder.[34] Furthermore, even at the range limit of few kilometers, the rangefinder's power consumption and weight/size are beyond the NM spacecraft capacity. Therefore, both line-of-sight (LOS) and range information must be obtained passively from a sequence of images. Note that stereo-vision[35] is not a consideration here because of the robustness issue and the unrealistic base-separation (distance between the two cameras) required to achieve the desired coverage.

Although the methodology research for AFAST can provide solutions for extracing the guidance signals from sequences of images, we feel that the dedicated hardware would be made more efficient by focusing on high bandwidth instead of broad functionality. The CE can be used to designate specific targets or features in the image plane, so only particular regions need foι eground tasking. Furthermore, there may be enough optical-characteristic differences between the CE and EGS (in terms of imaging celestial targets) to justify an independent sensing/processing device, since the CE would be designed for objects at a larger distance, from nearby solar system bodies (hundreds of kilometers away) to stars at infinity, while the EGS would not be concerned about stars, but would need to be able to image at close range (a few meters).

Immediate needs for NM missions (rendezvous, flybys, or orbiters) include the CE but do not include the EGS. Nevertheless, we want to broach this concept to the research communities whose applications and solutions may be synergistic with ours. For example, using optical processing to measure LOS rates while compensating the changes in camera rotation and range at video frame rate. (33 milliseconds per frame) to track military targets[36] may indirectly show the solution to the demanding processing requirements of the EGS for probes, landers, rovers, and sample-return spacecraft.

4. PROBABLE MISSION SCENARIOS

Figure 5 identifies the basic mission profile that represents various phases of target/star tracking for asteroid/comet rendezvous or flyby. Since radio metric measurements will not be used to locate the spacecraft position, NM spacecraft must rely on known orbits of Earth and the Moon, measured against background stars, to fix the 3-D spacecraft position. Known Solar System bodies such as Earth-crossing asteroids can be employed during cruise to triangulate the spacecraft position, and the targeted asteroid/comet can provide the target-relative position information for final GNC approach.[37] Star identification will be employed to establish spacecraft attitude, search for reference bodies, and identify reference stars for spacecraft position estimation. To keep the focus on the probable early mission scenarios for NM spacecraft, target tracking near the surface during the terminal guidance phase of hovering above or landing on the surface will not be discussed here.

It should be noted that in future spacecraft, all the imaging instruments will be hard-mounted for cost and reliability reasons, and thus spacecraft attitude control for those missions also implies instrument-pointing functions. Since the celestial-sensing system will not be able (o search independently for a cooperative star field like that of Canopus to establish spacecraft attitude, an all-sky, autonomous, star-identification capability will be a necessary requirement for every spacecraft GNCs ystcm.

In this section, we discuss the three important phases of NM missions (dcparture, cruise, and encounter) and their implications for hardware, software, and processing. During departure, the Earth and Moon, besides looking very bright (each more than 10,000 times brighter than the brightest star—Sirius), are large presences that CE will have to contend with. Simultaneous observations of the Earth or Moon and background stars will be quite a challenge for the CE, especially with a narrow field of view. Significant progress in both the sensing and processing technologies must be made to accommodate a wide range of brightness levels of celestial objects and extract the embcddcd guidance information, if a 3° field-of-view CE is to be employed during this stage. Since autonomous GNC without ground uplinks must be proven before the exploration visions for the 21st century can bc fully realized, thc first few missions may employ a wide-angle CE (30°-400) to reduce risk and computational/sensing burdens at the departure phase. Even with the 40° field, simple centroiding of the Earth image would not be advisable because of the presence of the terminator. Here, AFAST tools can be employed to provide a robust extraction of the Earth limb and accurately estimate its center for spacecraft position reference when the limb is measured against a background star, and the measurement is coupled with a similar Moon/star observation. Autonomous star-pattern recognition will also be needed to identify the stars that the Earth and Moon positions will be measured against. However, this will be relatively simple given the wide-field camera.

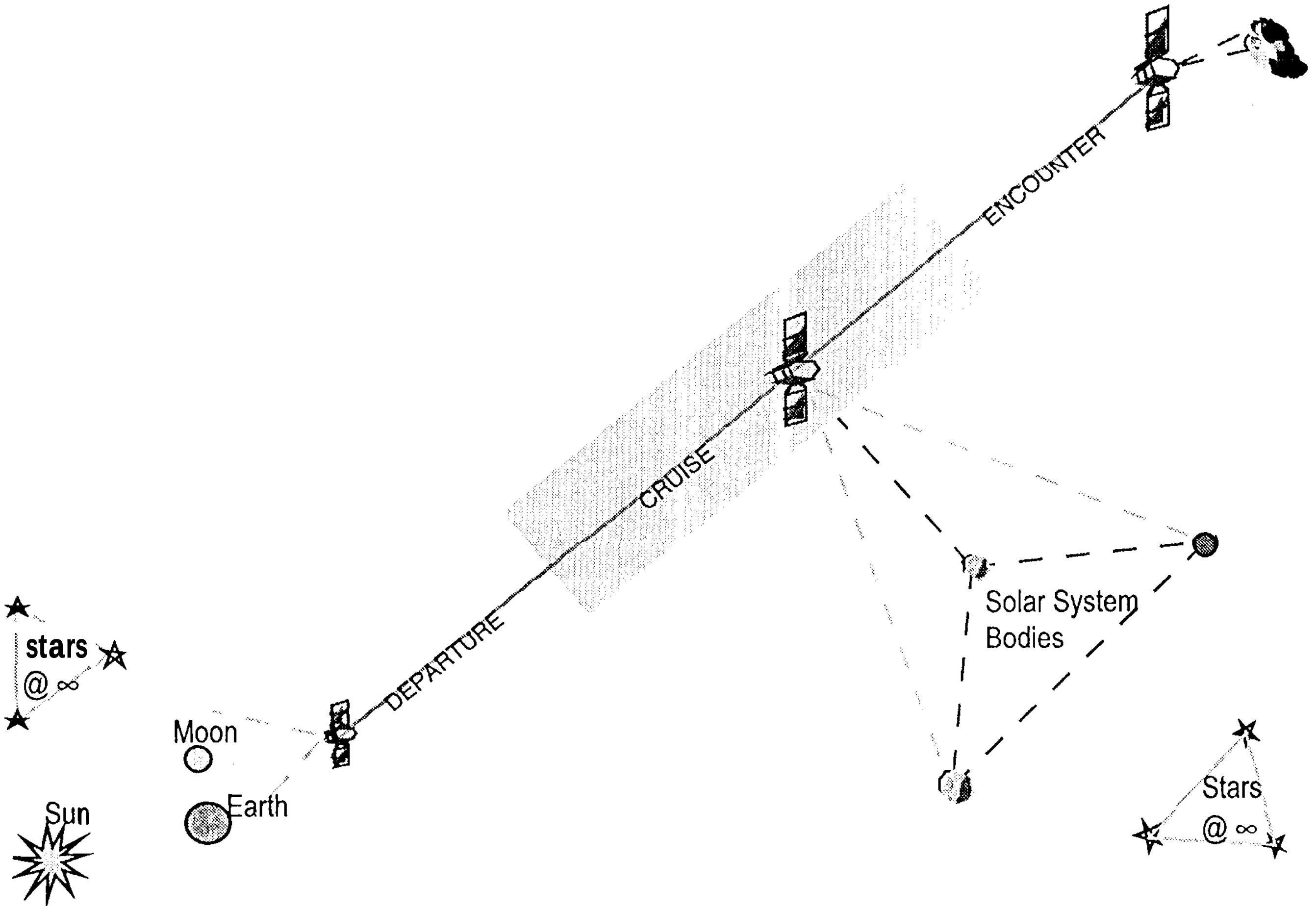


Fig. 5. NM spacecraft will employ both the knowledge of Solar System bodies and AFAST capabilities to navigate the spacecraft and carry out its mission autonomously, without ground intervention.

The cruise phase starts when the Earth and Moon become too small to provide accurate position information. If the destination is somewhere in the asteroid belt, the cruise distance can span 3-4 AU's (1 AU is approximately 150 million kilometers). Hence, the spacecraft trajectory must be carefully planned to ensure that its path crosses that of some of the many thousands of asteroids whose orbits have been cataloged. It is unlikely that a 40° field-of-view camera will be able to capture these faint and small (tens of kilometers or less) objects. Their brightness will depend on how closely the spacecraft can fly by these Solar System bodies; it may be in the 10th magnitude range. During this phase, a narrow-field CE (1°) would be preferred. Because of the small size and the irregular shape of asteroids, simultaneous target-body/star observations similar to Earth/star and Moon/star observations in the departure phase will not work. Three objects of known orbits sufficiently separated are needed during cruise to triangulate the spacecraft position. If we assume perfect orbital knowledge of these bodies, the accuracy of the triangulation will depend on the distance to these bodies and the errors in the angles of separation as measured from the spacecraft.

Because of the narrow field of view, three turns and accurate knowledge of these turns (their angular displacements) may be required, which means that better-performance gyros (a degree per hour drift rate may be adequate given a 10 field and 1-minute turn-period) or a stellar compass (which is a star tracker plus attitude estimation) will be needed. Viewing three bodies at different times and positions could present a problem. Nevertheless, a more demanding issue will be the detection of these bodies. The projection of star images onto the observed focal plane over a series of repeated observations will be needed to subtract background stars and confirm the capture of these Solar System bodies. As mentioned earlier, AFAST tools can be of assistance here in the detection of these objects, and further, they can characterize the shape if the object subtends over tens of pixels. Available AFAST solutions could, to some extent, assist in developing the GNC of a new navigation/pointing paradigm for the cruise phrase (just identifying Solar System bodies, managing large database of ephemerides, and accommodating search-and-find and fault conditions is already a handful).

The encounter period starts when the targeted asteroid/comet is captured in the field of view, and AFAST (the visual intelligence) can take over the tracking of the body, provide detailed characterization of its features, and estimate the viewing position. Note that AFAST only takes care of the sensory/perception aspect of the autonomous spacecraft. Pointing and AV maneuvers (commanding and execution) to carry out the rendezvous, orbiting, or other trajectory profiles must be done by the spacecraft GNC system, and the research germane to asteroid/comet GNC strategies based on line-of-sight and range information[38-39] has been limited. The smaller the field of view, the earlier the spacecraft can begin a precise target-relative GNC approach. However, smaller fields usually imply larger optics (because of the photon collection consideration). In addition, the smaller the field, the more difficult the search-and-find operations (which involve all the GNC components) to initiate the encounter phase. The wider the field, the greater the chance of capturing the target body too late. Therefore, some trade-offs must be made to find the optimal size for the camera parameters for this phase.

It is possible to derive a single CE to handle all the different phases of operation, but this vision will be achieved in later NM missions. Early missions must focus on demonstrating the ability to navigate the spacecraft through the Solar System without the use of conventional radio metric measurements and ground-based processing, and the use of multiple compact cameras to serve initially as the CE is prudent.

5. SUMMARY AND CONCLUSIONS

In this paper, wc have outlined a new capability that is essential to spacecraft guidance, navigation, and control and that relies on visual information instead of Earth-based position measurements. In addition, how Autonomous Feature And Star Tracking, or AFAST (which addresses the scene-interpretation capability specific to celestial images), can be incorporated in the New Millennium program is also described. There are many technical concerns that cannot all be addressed in this paper, and only critical issues were emphasized. In the final analysis, we hope that the following goals have been met:

•

1) Introduction to AFAST—AFAST **is** more than an algorithm development activity in a specialized computer vision field. Our goal is to make sure that AFAST solutions to flight issues culminate in innovative systems that will open a new avenue to the exploration of space.

2) Discussion of key technology for the New Millennium spacecraft—In support of NASA's New Millennium program, AFAST has a focussed direction to equip NM spacecraft with a capable "eye" to navigate their way to, and explore, Solar System bodies autonomously. This involves all aspects of engineering (sensors, processors, hardware, software, analysis, systems, integration, verification, and test), and working closely with the project to provide apposite planning and execution (a "technology roadmap") that will adequately serve NM visions is our priority.

3) Drawing participation from other researchers—AFAST technology development will be conducted in partnership with industry and universities. Synergism with the computer vision field was identified. However, to benefit space exploration in the 21st century, a plethora of solutions for celestial scene-interpretation and sensing systems must be accessible to candidate missions so that we can prevent falling back on obsolete technologies or creating new ones from scratch every time we plan a new mission.

If we insist on technologies that will lead to fully autonomous planetary spacecraft (i.e., no uplink requirements), NM missions will epitomize the space exploration of the future. More science data will be returned at a greater frequency with low-cost and highly capable spacecraft. There are many challenges and hurdles to overcome, but we feel that through cooperation and collaboration with universities, industry, and other research organizations, major breakthroughs will be made in this area,

6. ACKNOWLEDGMENTS

The authors would like to thank E. K. Casani (the New Millennium program manager) for his support of AFAST visions. His insight and constructive comments have contributed greatly to our success and the advancement of AFAST.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

7. REFERENCES

1. B. Bhanu, "Automatic target recognition: State of the art survey," *IEEE Trans. Aerospace Electron. Sys.*, Vol. AES-22, pp. 364-379, July 1986.
2. E. Krahn, H. Michalik, P, Rueffer, F. Gliem, K. Volk, and H. Reffel, "Tracking with the Giotto camera," *Zeitschrift fuer Flugwissenschaften und Weltraumforschung*, Vol. 14, pp. 183-192, June 1990.
3. "Autonomous feature and star tracking," JPL D-1 1758 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 1994.
4. R. M. Haralick and L. G. Shapiro, "Image segmentation technique," *Comput. Graphics Image Process.*, Vol. *29*, pp. 1OO-I 32, 1985.
5. L. Van Gool, P. Dewaele, and A. Oosterlinck, "Texture Analysis Anno 1983," *Comput. Graphics Image Process.*, Vol. 29, pp. 336-357, 1985.
6. J. R. Wertz, Ed., *Spacecraft Attitude Determination and Control,* Kluwer Academic Publishers, Dordrecht, The Netherlands, 1990,

7. S. Udomkesmalee, J. W. Alexander, and A. F. Tolivar, "Stochastic star identification," *J. Guidance, Control and Dynamics*, Vol. 17, pp. 1283-1286, November-December 1994.

8. C. Padgett and K. Kreutz-Delgado, "A grid algorithm for autonomous star identification, " submitted to *IEEE-AES*.

9. E. R. Davies, *Machine Vision: Theory, Algorithm, Practicalities,* Academic Press, San Diego, California, 1990.

10. C.-C. Chu, D. Q. Zhu, S. Udomkesmalee, and M. I. Pomerantz, "Realization of autonomous image-based spacecraft pointing systems: Planetary flyby example," *Proc. SPIE*, Vol. 2221, pp. 27-40, 1994.

11. S. P. Synnott, A. J. Donegan, J. E. Riedel, and J. A. Stuve, "Interplanetary optical navigation: Voyager Uranus encounter, " *AAIA/AAS Astrodynamics Conference*, Williamsburg, Virginia, August 1986.

12. R. M. Vaughan, J. E. Riedel, R. P. Davis, W. M. Owen, Jr., and S. P. Synnott, "Optical navigation: for the Galileo Gaspra encounter," *AAIA/AAS Astrodynamics Conference*, Hilton Head, South Carolina, August 1992.

13. S. Udomkesmalee, D. Q. Zhu, and C.-C. Chu, "Image processing foi Planetary limb/terminator extraction," submitted to *CVGIP*.

14. D. Dunn, W. E. Higgins, and J. Wakeley, "Texture segmentation using 2-D Gabor elemetary functions," *IEEE Trans. Pattern Anal. Machine Intell.*, Vol. PAMI- 16, pp. 130-149, February 1994.

15. C. Padgett and D. Q. Zhu, "Feature-based tracking and recognition for remote sensing," *Proc. SPIE*, Vol. *2466,* 1995.

16. S. Udomkesmalee and L. DeAntonio, "Detection of planetary terrain features," *Proc. SPIE*, Vol. *2466, 1995.*

17. *C. C.* Liebe, "A new strategy for tracking planetary terrains," *Proc. SPIE,* Vol. 2221, pp. 41-55, 1994.

18. R. O. Duda and P. E. Hart, *Pattern Classification and Scene Analysis,* Wiley, New York, 1973.

19. S. Udomkesmalee, G. E. Sevaston, and R. H. Stanton, "Toward an autonomous feature-based pointing system for planetary missions," *Proc. SPIE*, Vol. 1949, pp. 2-14, 1993.

20, P. S. Maybeck and D. E. Mercier, "A target tracker using spatially distributed infared measurements," *IEEE Trans. Automat. Contr.*, Vol. AC-25, pp. 222-225, April 1980.

21. J. Mason, Ed., *Cornet Halley,* Vol. *2, Ellis* Horwood, New York, 1990.

22. D. Q. Zhu and C.-C. Chu, "Characterization of irregularly shaped bodies," *Proc. SPIE*, Vol. *2466,* 1995.

23. D. P. Simonelli, P. C. Thomas, B. T. Carcich, and J. Veverka, "The generation and use of numerical shape models of irregular solar system objects," *Icarus,* Vol. 103, pp. 49-61, 1993.

24. T. C. Duxbury, "An analytical model of the Phobos surface," *Planet. Space Sci.*, Vol. 39, pp. 355-376, 1991.

25. J. Veverka, "The surfaces of Phobos and Deimos," *Vistas in Astronomy,* Vol. 22, pp. 163-192, 1978.

26. K. P. Klaasen, T. C. Duxbury, and J. Veverka, "Photometry of Phobos and Deimos from Viking orbiter images," *J. Geophys. Res.*, Vol. 84, pp. 8478-8486, 1979.

27. R. Y. Tsai and T. S. Huang, "Uniqueness and estimation of three-dimensional motion parameters of rigid objects with curved surfaces, " *IEEE Trans. Pattern AnaL Machine Intell.*, Vol. PAMI-6, pp. 13-27, January 1984.

28. R. M. Haralick and L. G. Shapiro, *Computer and Robot Vision,* Vol. II, Addison-Wesley, Reading, Massachusetts, 1993.

29. F. G. Meyer, "Time-to-collision from first-order models of the motion field," *IEEE Trans. Robotics and Automation,* Vol. 10, pp. 792-798, December 1994.

30. J. K. Aggarwal and N. Nandhakumar, "On computation of motion from sequences of images: A review, " *Proc. IEEE*, Vol. 76, pp. 917-935, 1988.

31. C. C. Clark, A. R. Eisenman, S. Udomkesmalee, and E. F. Tubbs, "Application of new technologies to future celestial trackers," *Proc. SPIE*, Vol. 2466, 1995.

32. V. T. Thomas, J. W. Alexander, E. W. Dennison, P. Waddell, G. Borghi, and D. Procopio, "Cassini star tracking and identification architecture, " *Proc. SPIE*, Vol. 2221, pp. 15-26, 1994.

33. J. Cuseo and C. Dallas, "Planetary terminal descent simulation with autonomous hazard avoidance," *AIAA Aerospace Sciences Meeting,* Reno, Nevada, January 1989.

34. C. S. Fox, Ed., *Active Electro-Optical Systems,* SPIE Optical Engineering Press, Bellingham, Washington, 1993.

35. J. E. W. Mayhew and J. I'. Frisby, Eds., *3D Model Recognition for Stereoscopic Cues,* MIT Press, 1991.

36. J. A. Sloan and L. A. Holloway, Jr., "A self-servoing optical correlator for tracking," *Proc. SPIE*, Vol. 1151, pp. 307-317, 1989.

37, S. P. Synnott, "Optical-only navigation," JPL Interoffice Memorandum #314.8-898/SPS (internal document), April 1994.

38. M. Noton, S. V. Salehi, and C. A. Elliot, "Low thrust navigation for a comet-nucleus sample-return mission, " Second *International Symposium on Spacecraft Flight Dynamics (ESA)*, Darmstadt, Germany, October 1986.

39. M. Guelman, "Guidance for asteroid rendezvous," *J. Guidance, Control and Dynamics,* Vol. 14, pp. 1080-1083, 1991.